Enabling High Capacity Flexible Optical Networks

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Abstract— **Current bandwidth demands are encouraging the exploration of optical frequency comb generators and flexible modulation formats to enable very high-capacity transmission beyond the C-band, which can be augmented with existing real-time digital electronic signal processing for pre-emphasis and post-impairment compensation at very high clock speeds. But for exploitation and deployment in commercial networks these devices will require support for remote management embedded with service providers' operation and business-support systems. However, installed network management systems must deal with a range of dissimilar network devices. This diversity spans across electronic packet switches, optical circuit switches, and monitoring instrumentation for telemetry, ranging from legacy to state-of-the-art models. Software defined networking (SDN) flexible management approach unlocks exciting possibilities to jointly exploit the full capabilities of digital electronic packet switching and the many degrees of freedom presented by analogue optical EM carriers. In this paper, we will expose some of these possibilities, where these technologies can, through SDN, be reimagined to enable flexible high-capacity systems. We will be revisiting the potential for multi-carrier transmitters, and utilising analogue methods to monitor transmitter performance. We will also show how existing protocols can be used to support both legacy and state-of-the-art SDN-enabled devices, incorporating to management operating systems such as ONOS, showing that a smooth transition to fully automated networks with closed-loop control is now a real prospect.**

Keywords— multi-carrier, SDN, flexible networks

I. INTRODUCTION

Two decades ago, NTT demonstrated all-optical orthogonal frequency division multiplexing (OFDM) of optical carriers for high spectral efficiency transmission [1]. The ideas that followed extended its implementation to utilising coherent (or semi-coherent) optical carriers from comb generators or phase-locked laser transmitters, enabling techniques such as Coherent WDM [2] and Nyquist WDM [3], sometimes also called superchannels. Such technologies exploit well-known tools such as Fourier Transforms and the Sampling Theorem to generate high capacity multi-carrier channels. By reducing frequency spacing between optical subcarriers below standard 50GHz, it increases spectral efficiency, especially if used in combination with complex modulation formats such as mQAM together with polarisation multiplexing. State-of-the-art transceivers already operate with "multi-lanes" to enable 400G, 800G and potentially 1.6Tbit/s [4], so the next step is likely to require multi-carrier solutions such as Coherent WDM or Nyquist WDM. The challenge this past decade has been on enabling photonic integration of these concepts for practical implementations, with the aid of Silicon photonics [5], heterogeneous integration [6], and high speed electronics [7]. The challenge this decade, however, will be commercial exploitation: how to transfer these hardware technologies from the laboratory bench to practical deployment. Now is an opportune time to consider how best to assemble and package these hardware techniques and devices for commercial network equipment, and embed them with business-support systems.

SDN has matured sufficiently in recent years to hasten this trend because the barrier-to-entry has been lowered to allow research to occur outside of commercial vendors. The software technologies that SDN has provided have allowed the disaggregation of the management, control, forwarding, operational and applications layers using Open APIs [8]. These Open APIs allow easier integration with the control, management and orchestration systems of network operators. But such software innovations have mainly focussed on electronic digital packet switched devices; with less attention, however, in considering optical analogue carrier switched devices. The analogue optical layer is often seen as an "opaque client" that is quite distinct and separate from electronic digital packet switching. But this is also changing. SDN-enabled Open Transponders and Open ROADMs have been commercially available for the several years to provide greater flexibility, resilience and path restoration [9]. Flexible transponders allow baud rate and modulation formats to be varied quasi-statically to accommodate changes to transmission distance. And within this context, we could take a step further and control the manipulation of optical carriers on demand from multi-carrier coherent optical channels. Such open-loop control allows high capacity to be provisioned when needed, or the channel capacity to be reduced when necessary, simply by adding (or removing) subcarriers. In addition, analogue techniques that enable pulse or spectral shaping could also be added either to maximise performance or to optimise energy consumption. This is an important consideration as excess heat generated has to be vented efficiently; the budget to deliver power (per square metre) to a device and dispose of excess heat (per cubic metre) can be a major constraint for network operators. SDN will help here by having more latitude when designing and developing digital and analogue logic circuits, to minimise the energy consumption and heat generation. The power draw and heat dissipation load is a function of the number of concatenated digital operations (or taps). Simplification of the DSP with analogue control substitution can alleviate energy usage.

In this paper we outline three aspects for consideration: spectral shaping of multi-carrier superchannels; real-time monitoring of modulator performance; and the abstraction and control of disaggregated (legacy) hardware devices that lend themselves for deployment in high-capacity optical networks. Firstly, we show the use of adaptive optical filtering of superchannels using wavelength selective switches. These can form and optimise implementation for deployment in optical transmission networks. Secondly we show an analogue DC bias control system for Mach-Zehnder modulators. These are a necessary component for flexible comb generation techniques and complex IQ modulation. Thirdly, we outline how any device may be managed and controlled with

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OpenAPIs, combined with hardware and software disaggregation. The YANG modelling language can be adopted to provide the abstraction of such disaggregated and legacy devices.

II. PHYSICAL LAYER TECHNOLOGIES

A. *Spectral shaping of Multi-carrier Channels*

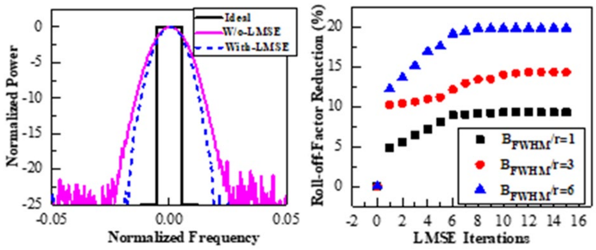

Figure 1: Example LMSE spectral shaping. (left) comparison of ideal filter shape (rectangle), shaping after WSS (solid line), and after LMSE algorithm (dashed line). (right) Roll-off factor improvement for each iteration, for a number of filter widths.

Spectral shaping plays a crucial role in high capacity optical networks as it allows carrier spacing to be reduced, in comparison to standard DWDM systems, resulting in increased spectral efficiency, and also alleviating the impact of transmission impairments. Spectral shaping has been extensively shown in the digital domains, or in simulations with off-line processing. In real implementations, such digital filters require ultra-high-speed digital-to-analogue converters (DACs) and high-speed digital-signal-processing (DSP). To enable precise shaping and roll off, it requires complex electronic/digital circuits, requiring many taps, which increases footprint, costs and energy requirements. However, if we implement cost-effective analogue techniques, side-by-side with digital solutions, some of these challenges can be overcome. For example, here we used a wavelength selective switch (WSS) for spectral shaping at the transmitter side [10]. The advantage of using such filters transcend beyond the optical profiling itself, as WSS are the core of ROADMs, and they are widely available for abstraction and control in SDN. An ideal roll-off in Nyquist WDM would be close to zero as possible, which would indicate a very square-spectrum filter profile. However, for superchannels close to the Nyquist limit, it is practically impossible to obtain a zero roll-off modulated spectrum.

So our proposed tool adapts the spectral roll-off-factor of programmable optical filters for optical shaping of superchannels using a WSS and a least mean square algorithm, achieving a significant (19.8%) reduction in roll-off-factor. Implementing such adaptive optical filters at the transmitter will help reduce the complexity (or the number of filter taps) required in the electronic/digital domain. As a comparison, filters with a large number of taps are commonly used for digital pre-shaping. For example, reducing a roll-off factor from 0.1 to 0.01 for a 16-QAM based Nyquist WDM system needed 1000 taps implemented with offline processing [11]. So simplification is needed.

The concept of our work relies on the principle of a well-known feedback-based optimization method: Least Mean Square Error (LMSE) algorithm. LMSE algorithm serves the purpose to reduce the MSE between the desired filter shape and the measured WSS filter shape output. LMSE can help re-shape the output profile closer to the desired shape by a few iterations when configuring the transmitter, in a "set and forget" scenario; re-uploading a new filter shape into the programmable optical filter, which produces a new output that has a more accurate representation of the desired filter profile. Figure 1 shows a typical example, where a significant improvement in roll-off factor is obtained even after 1 iteration, but typically requiring 6 iterations for optimum improvement. Figure 1 (right) also shows that, depending on the resolution (r) of the WSS used and the required filter bandwidth (B_{FWHM}), the best roll-off factor achievable will differ. In our experiments, we were limited to a WSS resolution of 10GHz, varying the bandwidth (i.e. WSS channel bandwidth) between 10 and 60 GHz. The technique shows that it is possible to help DSP utilising a WSS as a programmable filter in configurable networks. This is an interesting add-on to the hardware abstraction and management layer, where shaping can be re-configured depending on the reach and/or transmission needs.

B. *Real time monitoring of MZMs*

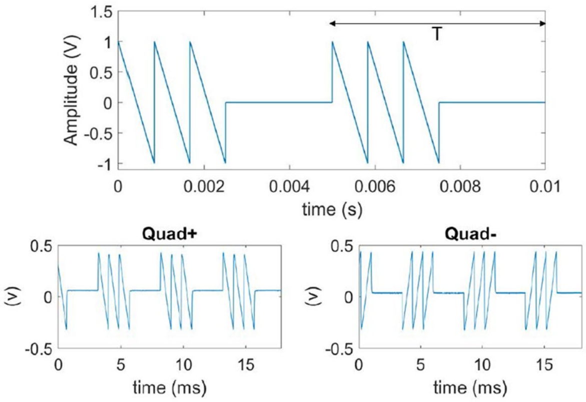

Figure 2: (upper) Time-interleaved DC bias dither signal. (lower):MZ biased a quadrature, with positive slope (left) and negative slope (right).

Mach-Zehnder (MZM) are commonly used in high capacity optical systems, especially for data encoding in dual-polarization and for IQ modulation; but also in flexible comb generation schemes. Optimum performance is highly dependent on the DC biases of the modulator, and there are a few commercial systems, and several research solutions, proposed to compensate for bias drifts. The most common approach is on the reliance of integrated photodiodes for power monitoring. This is particularly important for nested MZs or IQ modulators, which are more difficult to monitor due to their complex configuration. However, scaling towards multi-channel multi-modulator integrated devices utilising such approach may be quite difficult. Challenges such as avoiding channel crosstalk, or increase of footprint, can be very difficult to solve. Hence, solutions that avoid these extra detectors, in particularly when multiple nested MZ modulators are required (such as the case in superchannels), would be favorable and of benefit. With this in mind, we studied an analogue DC bias monitoring scheme that can be implemented for single modulators and scalable to multiple nested MZMs [12]. The scheme is based on the application of low-speed analogue dither signals to the DC bias, which are time interleaved to ensure that each dither can be detected independently using a single low-speed photodetector at the output of the device.

An example of dither signal is shown in Figure 2 (upper). A sawtooth was used as a dither signal, interleaved with a null signal. This signal is then applied to one MZM, say "I".

Another dither, with different frequency and shifted by T/2 could then be applied to another modulator, say "Q" (not shown). Hence, both signals could be independently monitored at the output of the IQ modulator utilizing a single detector. Variations in the amplitude of the measured signal can determine if each modulator is biased at the minimum, quadrature or maximum values of its transfer function. The two lower pictures of Figure 2 show the measured monitoring signals out of a single MZM when biased at quadrature. Here's where utilising a sawtooth is of interest: when monitoring the quadrature bias point at the rising slope of the transfer function (Quad+), the sawtooth is reproduced. However, when biased at the falling edges (Quad-), the sawtooth is flipped. Monitoring the DC bias of MZM is of critical importance as it can deteriorate the quality of the signal, and hence its performance over transmission. As the proposed system relies on analogue signal monitoring, it can be an important real-time telemetry tool to feed back to the control management to ensure optimum performance and to raise alerts.

C. *Hardware abstraction of disaggregated devices for telemetry*

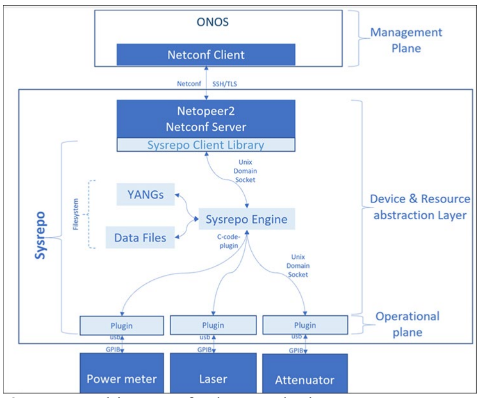

Figure 3: SDN architecture for legacy devices.

While state-of-the-art open-ROADMs, open-switches and transponders can be easily abstracted into control and management planes, certain telemetry efforts, for example real-time OSNR per channel analysis, may require additional resources and hardware. Our results with the MZM DC bias monitoring is one of these cases, where bespoke telemetry could be incorporated to the management plane, but such platform does not exist. Hence, we decided to use legacy devices, such as power meters and attenuators, as a proof-of-concept challenge on integrating such devices with an SDN platform. The key challenges were (a) the physical connection to the device; (b) to ensure that drivers were in place to enable "hand-shake"; (c) to develop new YANG-models; (d) to control devices through CLI commands.

Figure 3 shows the schematic of the SDN stack developed, which is an example for potentially managing and controlling any device. Besides the usual connectivity drivers, such as GPIB and USB, a datastore, such as Sysrepo, had to be used in order to connect to the Netconf server via Netopeer [13][14]. A bespoke YANG model was created for this too. To test this proposed architecture, a simple loop experiment was set up comprising of a bench-top attenuator and power meter. We used a packet generator and an SFP as source. The output of the SFP was looped back via the attenuator to emulate an optical fibre link. By changing the attenuation with the CLI command, we could measure the received data with the packet generator. Virtually no frames were lost until attenuation was increased to ~17.5dB, which is equivalent to ~80km of SMF, in line with the SFP specification. This simple experiment demonstrate that any optical device can be managed and controlled by an SDN architecture. This could certainly help with the control awareness of the physical layer and assist with routing assignments.

III. CONCLUSION

In this paper, we have shown potential paths for integrating optical devices flexibility through SDN. We revisited the potential for multi-carrier transmitters and flexible adaptive filtering in the transmitter-side; we demonstrated the potential for analogue monitoring of modulators; and we have also shown how existing protocols can be used to support legacy SDN-enabled devices, incorporating to management operating systems such as ONOS. Much more needs to be done, but perhaps these are the first steps towards fully automated networks with closed-loop control.

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